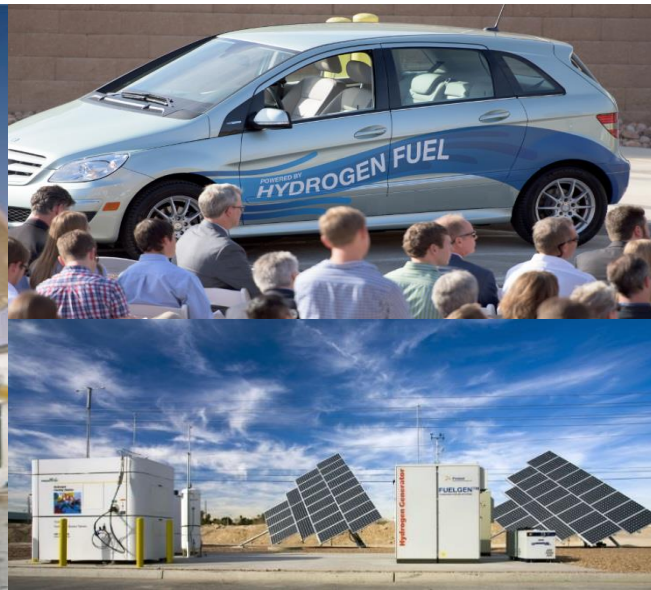


H2@Scale for Decarbonizing Heavy Industries

Dr. Eric L. Miller

Senior Advisor, U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office

Industrial Decarbonization: Renewable Process Heating from Concentrating Solar Thermal, September 14, 2021



President Biden and Energy Secretary Granholm at Climate Summit



“...I’ve asked the Secretary of Energy to speed the development of critical technologies to tackle the climate crisis. No single technology is the answer on its own because every sector requires innovation to meet this moment.”

*President Joseph R. Biden
April 23, 2021*



Launch of Hydrogen Energy Earthshot
First of the Energy Earthshots
June 7, 2021
at DOE Hydrogen Program Annual Merit Review

*Secretary Jennifer Granholm
June 7, 2021*



Hydrogen

Hydrogen Shot

"1 1 1"

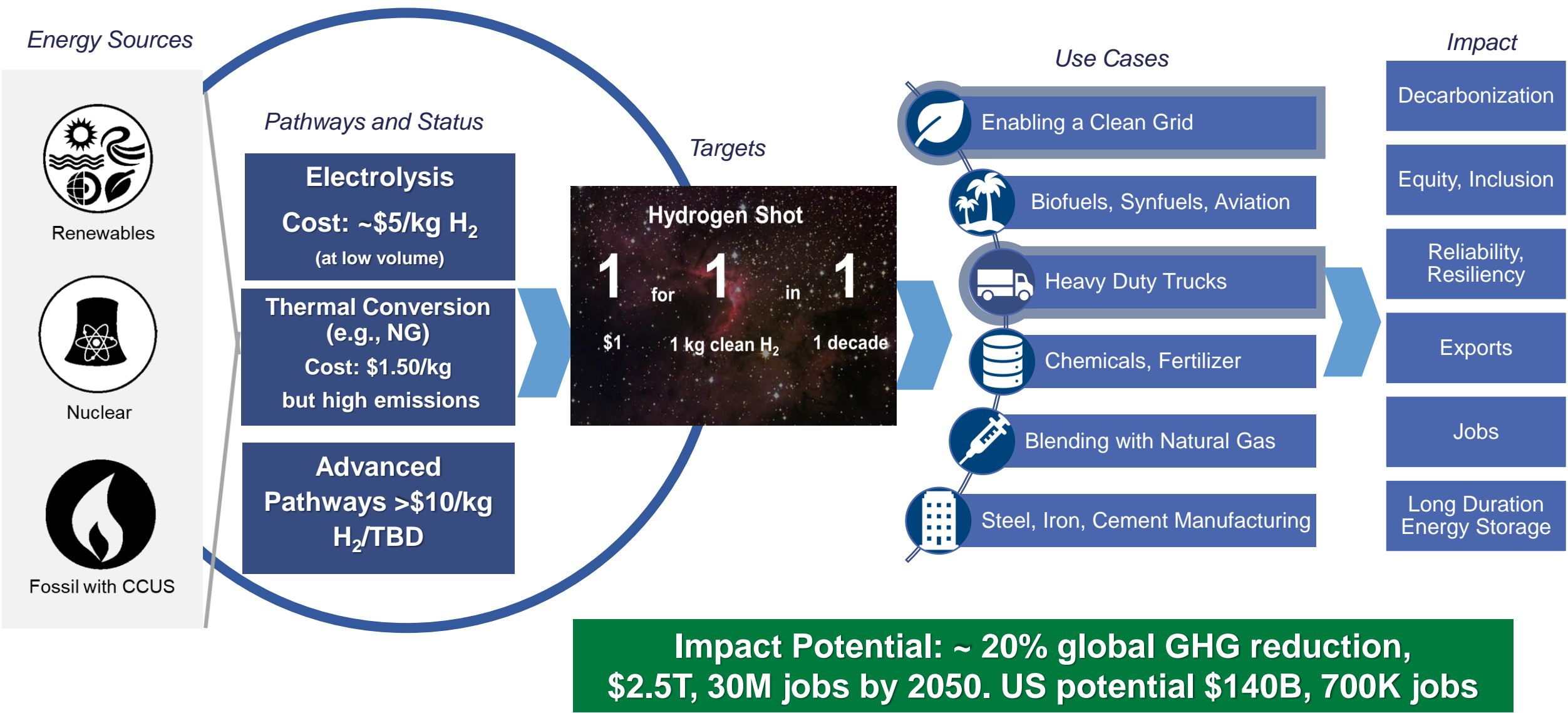
\$1 for 1 kg of clean hydrogen in 1 decade

Launched June 7, 2021

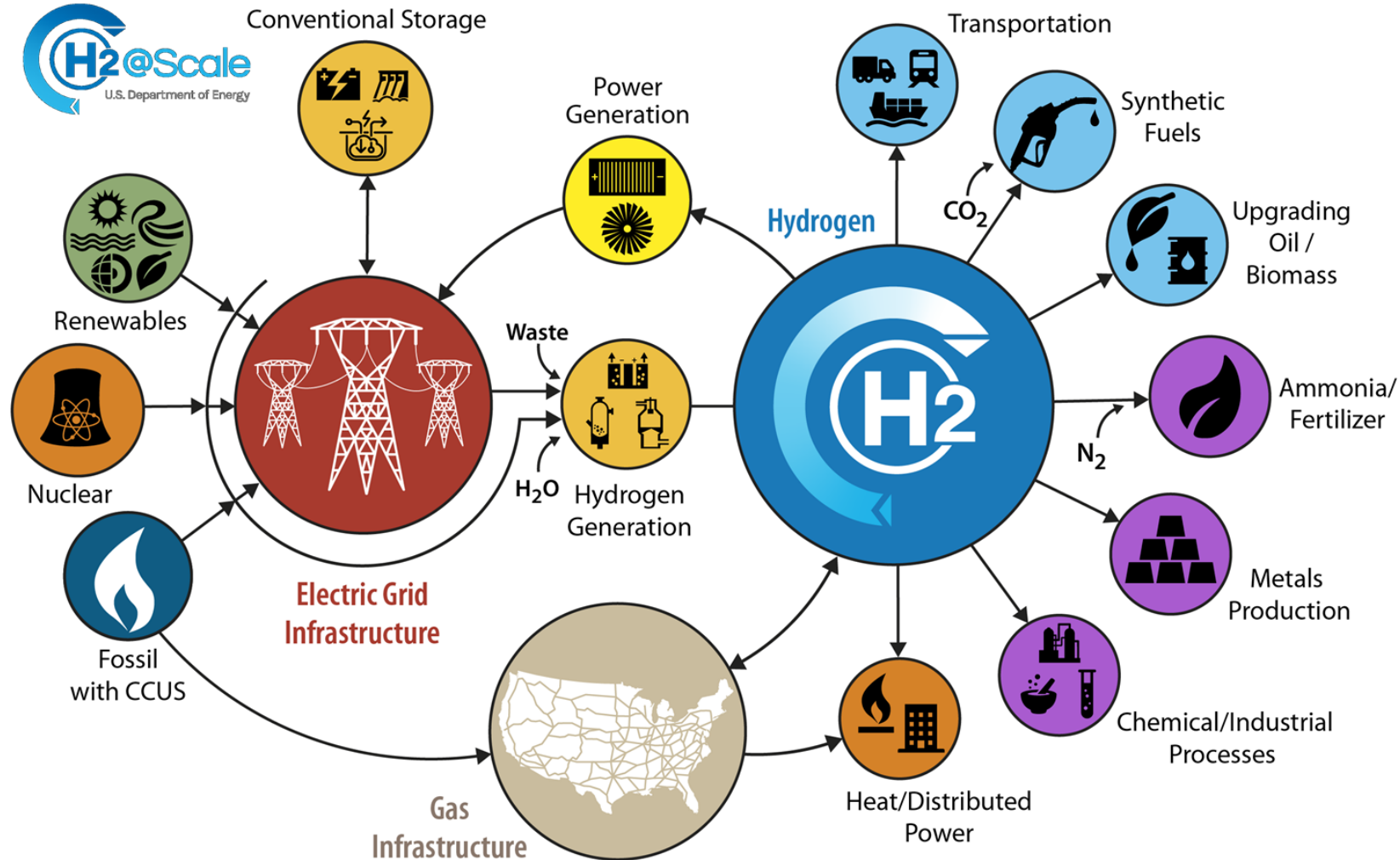
*First Hydrogen Shot Summit
on August 31 – September 1, 2021*



Hydrogen Shot: Environmental and Economic Impacts



H2@Scale for Deep Decarbonization, Economic Growth, & Jobs



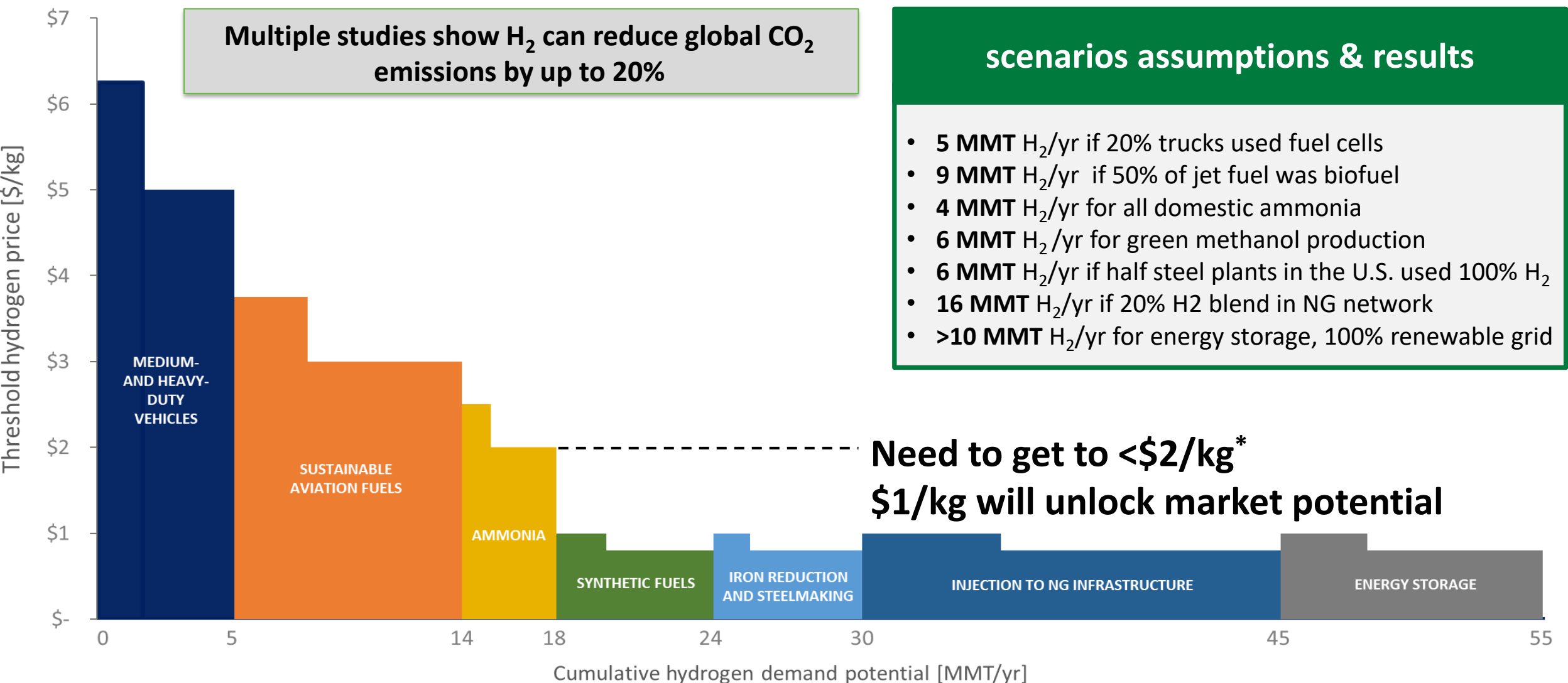
Key Opportunities

- **Hard to decarbonize sectors**
 - Steel, cement, ammonia
 - Heavy duty and trucks
 - Sustainable aviation fuels
- **Energy storage and blending**
- **Export potential**

• 10 MMT of H₂/yr produced in the U.S. today

- Would ~ double today's solar or wind deployment
- Significant projected growth potential (>2-5X)

Market Potential Scenarios with Cost Tipping Points






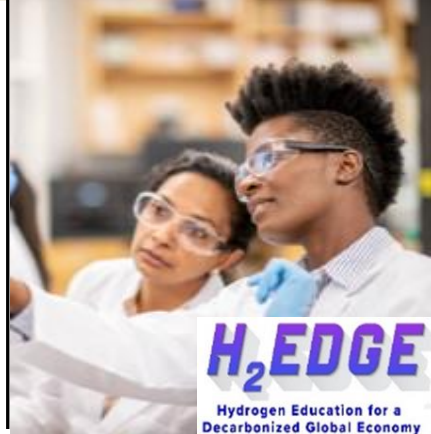


H₂ cost for trucks includes delivery and dispensing






Results based on preliminary analysis. Updates underway.

H2@Scale: Focus on Demonstration & Workforce Training

Different regions, hydrogen sources, end uses & educational opportunities

H₂ for Marine Application	H₂ from Renewables	H₂ for Data Center
 <p>California</p> <p>1st-of-its-kind maritime H₂ refueling on floating barge - up to ½ ton H₂/day</p>	 <p>Texas</p> <p>Integrates wind, solar, RNG from waste with onsite electrolysis and multiple end-uses</p>	 <p>Washington</p> <p>Integrates a 1.5MW fuel cell with a data center to provide reliable and resilient power</p>
H₂ for Steel Production	H₂ from Nuclear Energy	Workforce Development
 <p>Missouri</p> <p>Reduction of 30% in energy and 40% emissions vs. conventional processes</p>	 <p>New York</p> <p>Demonstrates a MW electrolyzer with a nuclear plant (collaboration with Nuclear Office)</p>	 <p>Multi-state</p> <p>A Training, education and recruiting program to build skills needed in the H₂ industry</p>

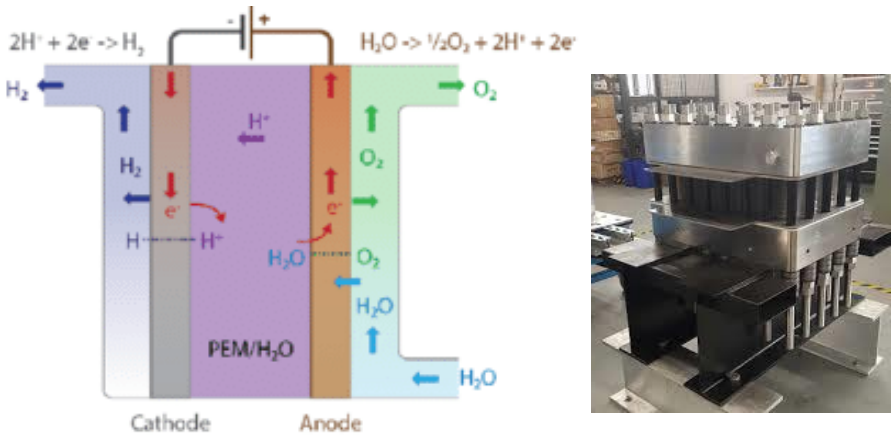
Clean H₂ Production from Diverse Domestic Resources

FOSSIL RESOURCES	BIOMASS/WASTE	H ₂ O SPLITTING
<ul style="list-style-type: none">• Low-cost, large-scale hydrogen production with CCUS• New options include byproduct production, such as solid carbon <div><div>Coal Gasification with CCUS</div><div>Natural Gas Conversion with CCUS</div><div>SMR</div></div>	<ul style="list-style-type: none">• Options include biogas reforming and fermentation of waste streams• Byproduct benefits include clean water, electricity, and chemicals <div><div>Biomass Conversion</div><div>Waste to Energy</div><div>ADG</div></div>	<ul style="list-style-type: none">• Electrolyzers can be grid-tied, or directly coupled with renewables• New direct water-splitting technologies offer longer-term options <div><div>STCH</div><div>Direct-Solar</div><div>High Temp. Electrolysis</div><div>Low Temp. Electrolysis</div><div>PEC</div><div>Electrolysis</div></div>

Conversion efficiencies are key : thermal integration & optimization offers important benefits

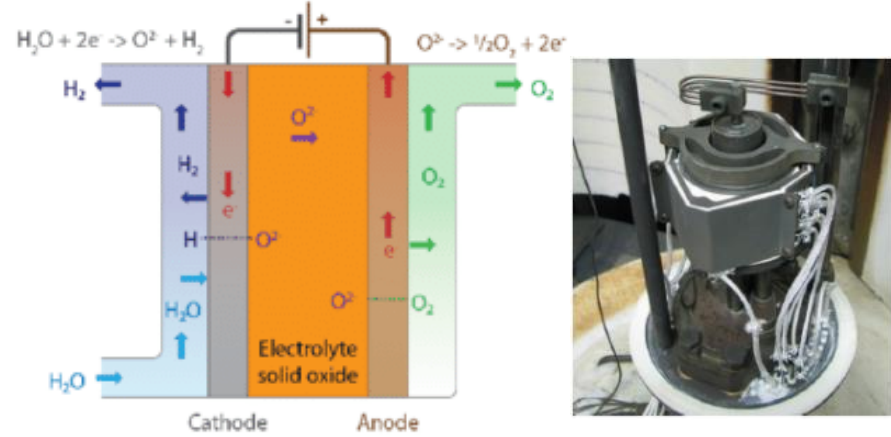
Hydrogen Production by Water Electrolysis

Low-temperature electrolysis



Example: Polymer Electrolyte Membrane (PEM)	
Charge Carrier	H ⁺
Temperature	20° - 80° C
Anodic Reaction	2H ₂ O → 4H ⁺ + O ₂ + 4e ⁻
Anode	IrO ₂ (or mixed Ir/Ru) / TiO ₂ supports
Cathodic Reaction	4H ⁺ + 4e ⁻ → 2H ₂
Cathode	Pt / C
Electrical Efficiency	~60 – 70 %
Status: Commercialized	

High temperature-electrolysis

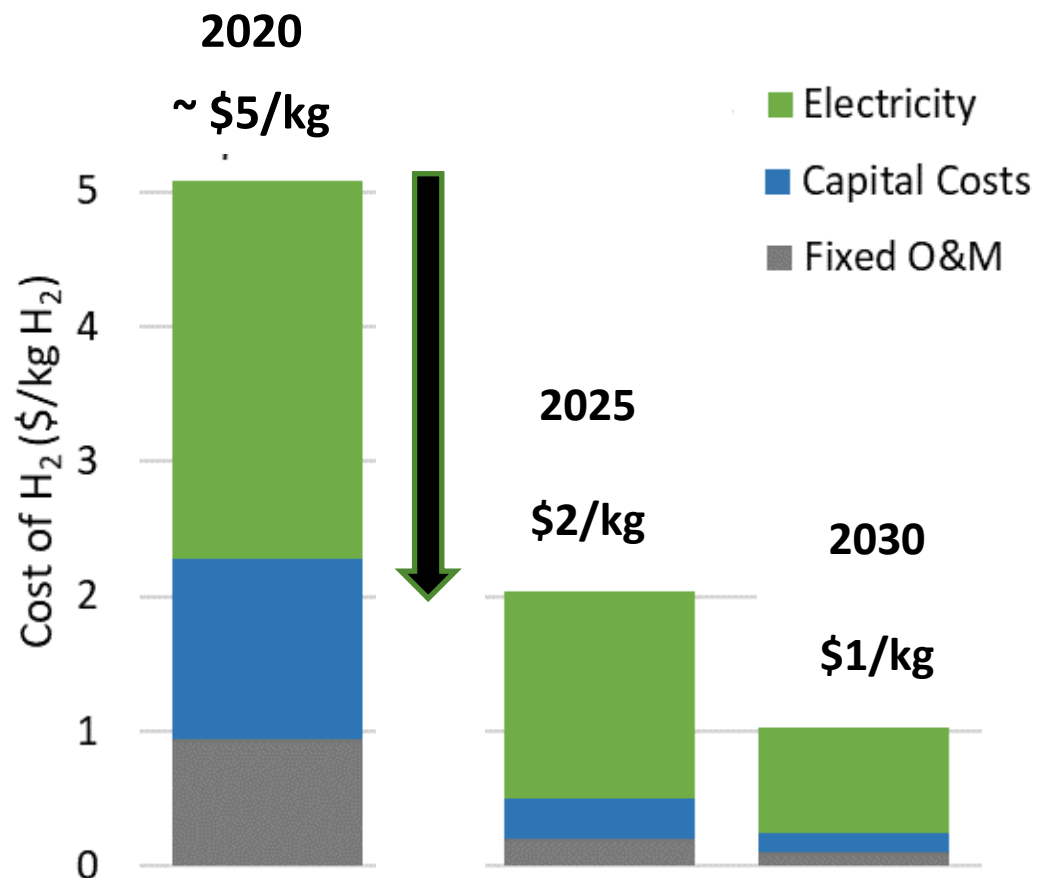


Example: Solid Oxide Electrolysis Cells (SOEC)	
Charge Carrier	O ²⁻
Temperature	500° - 1000° C
Anodic Reaction	O ²⁻ → ½ O ₂ + 2e ⁻
Anode	La _x Sr _{1-x} MnO ₃ + YSZ
Cathodic Reaction	H ₂ O + 2e ⁻ → H ₂ + O ²⁻
Cathode	Ni- YSZ / LaCrO ₃
Electrical Efficiency	> 90 %
Status: Demonstration	

Thermal integration offers benefits, especially in high-temperature electrolysis

Pathways to the Hydrogen Shot Target of \$1/kg

Example: Cost of Clean H₂ from Renewable PEM Electrolysis: One Pathway to the Target



2020 Baseline: PEM low volume capital cost ~\$1,500/kW, electricity at \$50/MWh. Need less than \$300/kW by 2025, less than \$150/kW by 2030 (at scale)

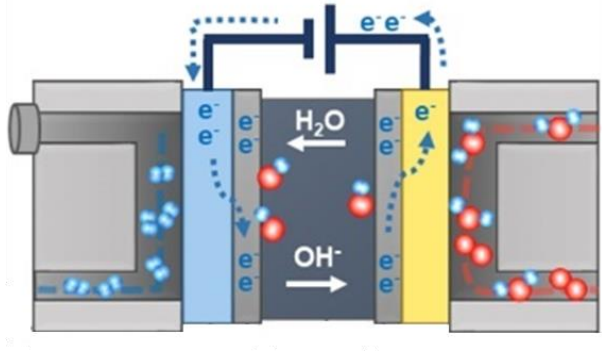
- Reduce electricity cost from >\$50/MWh to
 - \$30/MWh (2025)
 - \$20/MWh (2030)
- Increase conversion efficiency to >70%
- Reduce capital cost >80%
- Reduce operating & maintenance cost >90%

All approaches for clean hydrogen included:
Thermal conversion with CCS, advanced water
splitting, biological approaches, etc.

High conversion efficiency is a key factor: solar/thermal integration can play an important role

Other Important Clean H₂ Production Pathways

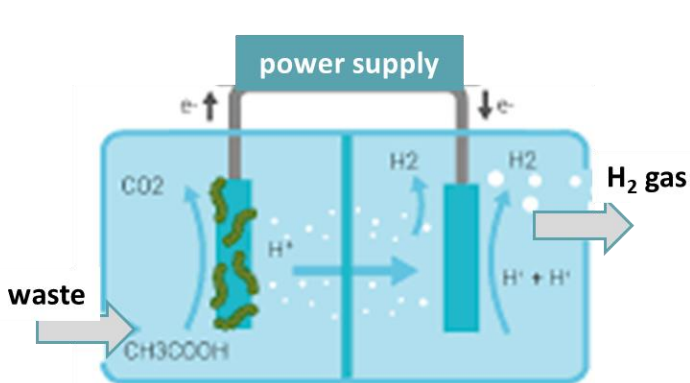
Next-generation water electrolysis



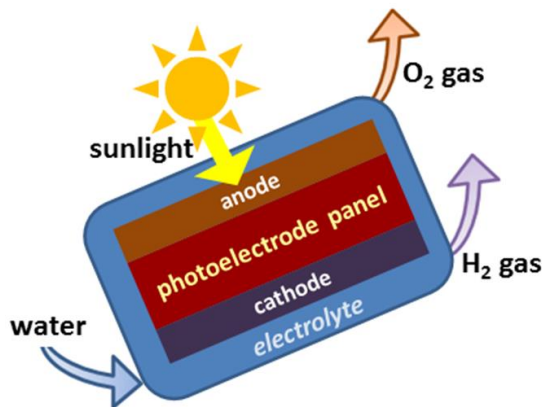
Next-generation production from NG with CCUS



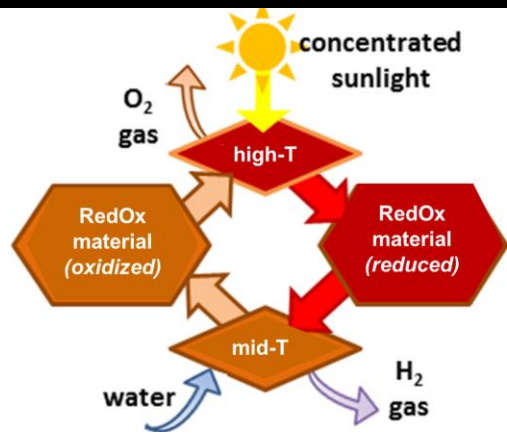
Microbial production from waste



Photoelectrochemical water splitting



Thermochemical water splitting



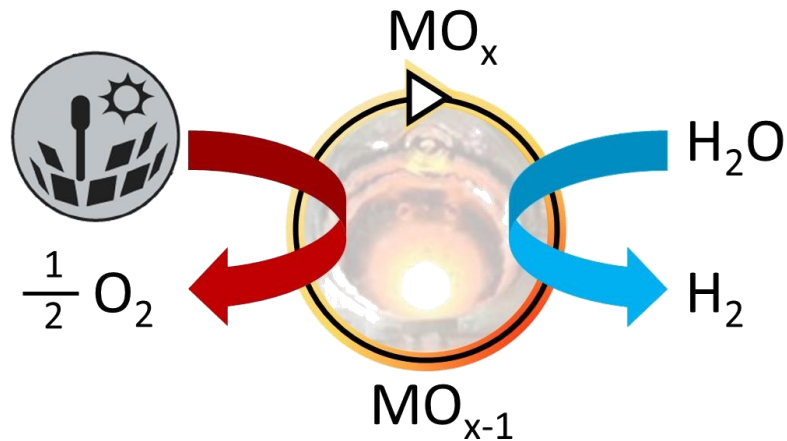
Solar / thermal integration benefits possible across all pathways

Thermochemical Water Splitting Cycles



A. McDaniel: SNL

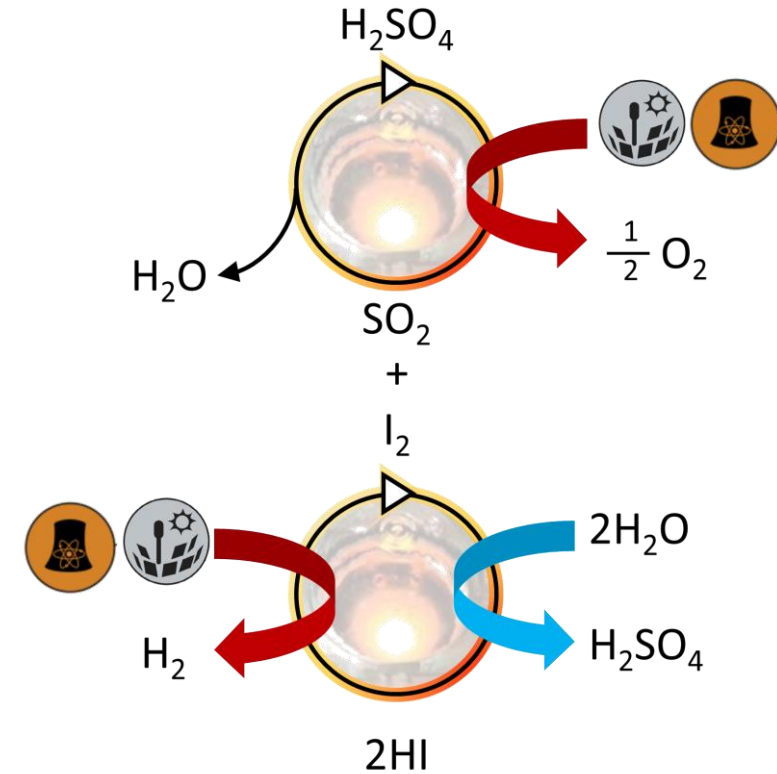
M = Ce, Sn, 1st row transition metal, Zn group metal
MO_x = fluorite, perovskite, spinel, two-phase systems



- **Two-step metal oxide cycles:**

- Change oxidation state of a single element
- Stoichiometric or non-stoichiometric
- May undergo phase changes (s, l, v, cryst)

High process temperatures ($T > 1500\text{ }^{\circ}\text{C}$)



- **Multi-step cycles:**

- Change oxidation state of two or more elements
- Multiple chemical species reacting in each step
- Several hundred cycles have been proposed

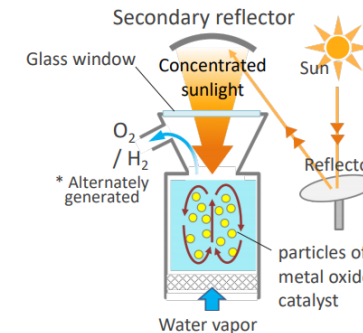
Moderate process temperatures ($T < 1000\text{ }^{\circ}\text{C}$)

Global Pursuits to Collaboration and Scaling Up

- **Hydrosol project: world's largest solar thermochemical H_2 plant**
 - DLR (Germany), CIEMET (Spain), HYGEAR BV (Netherlands), and ELLINIKA PETRELAIA AE (Greece)
 - Two-step metal oxide cycle @ 750 kW_{th}
- **Joint solar thermochemical hydrogen R&D**
 - ARENA (Australia) and Niigata University (Japan)
 - Two-step metal oxide cycle @ 500 kW_{th}
- **Iodine sulfur process for hydrogen production**
 - Japan Atomic Energy Agency
 - $100\text{ NL/hr } H_2$ test facility using industrial structural materials
- **Particle receiver design of solar thermochemical fuels**
 - Sandia National Labs (USA) and DLR (Germany)
 - Two-step metal oxide cycle @ 50 kW_{th}



<https://www.solarpaces.org/worlds-largest-solar-reactor-will-split-h2o-hydrogen/>



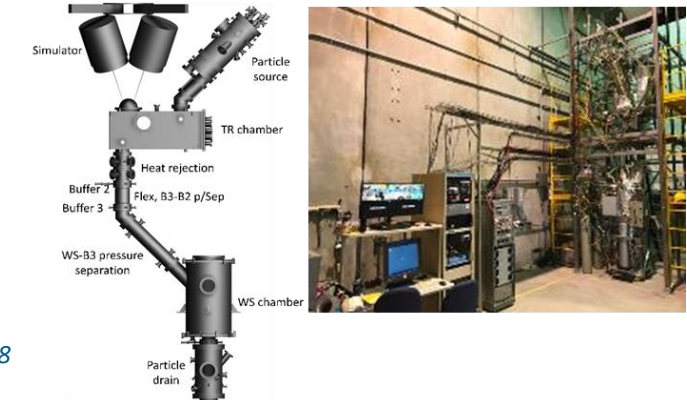
<https://arena.gov.au/projects/solar-thermochemical-hydrogen-research-and-development/>



CSIRO's 500kW class solar concentrating system to be used in the project.



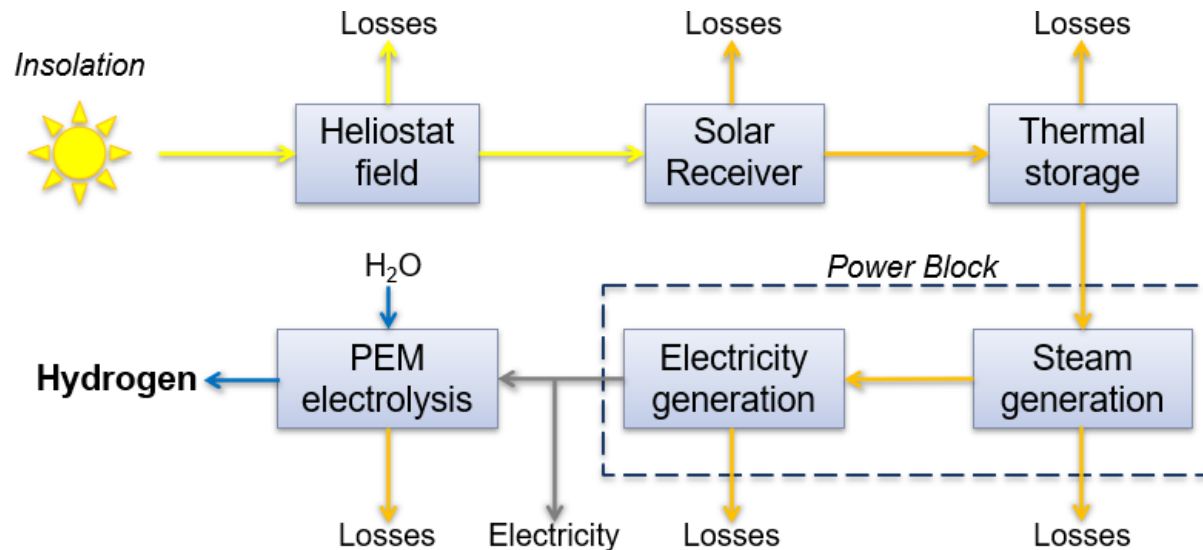
<https://doi.org/10.1016/j.nucengdes.2019.110498>



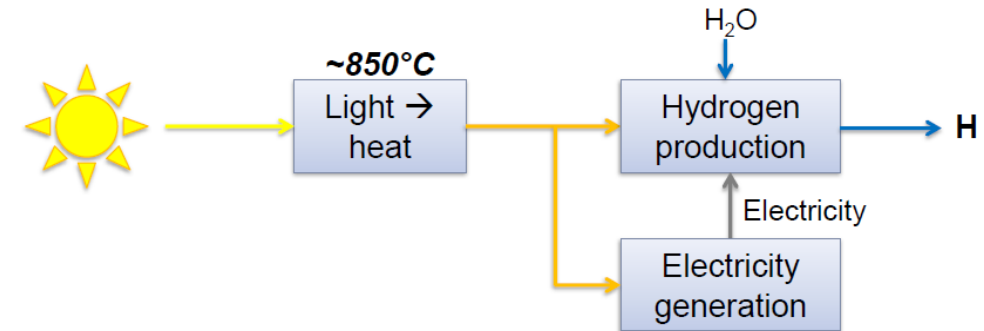
Targeting large scale production plants that offer advantages in efficiency and cost

Exploring Optimal Combinations of CSP and H₂

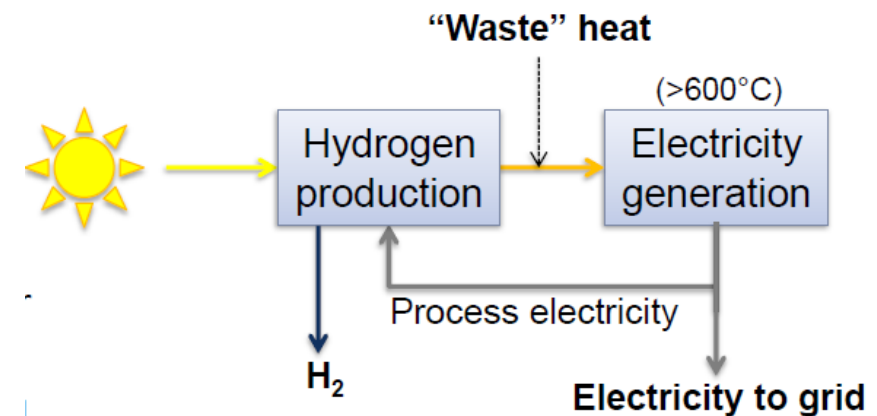
Baseline Case: CSP electricity + PEM electrolysis



Example Case: CSP + high-temperature electrolysis



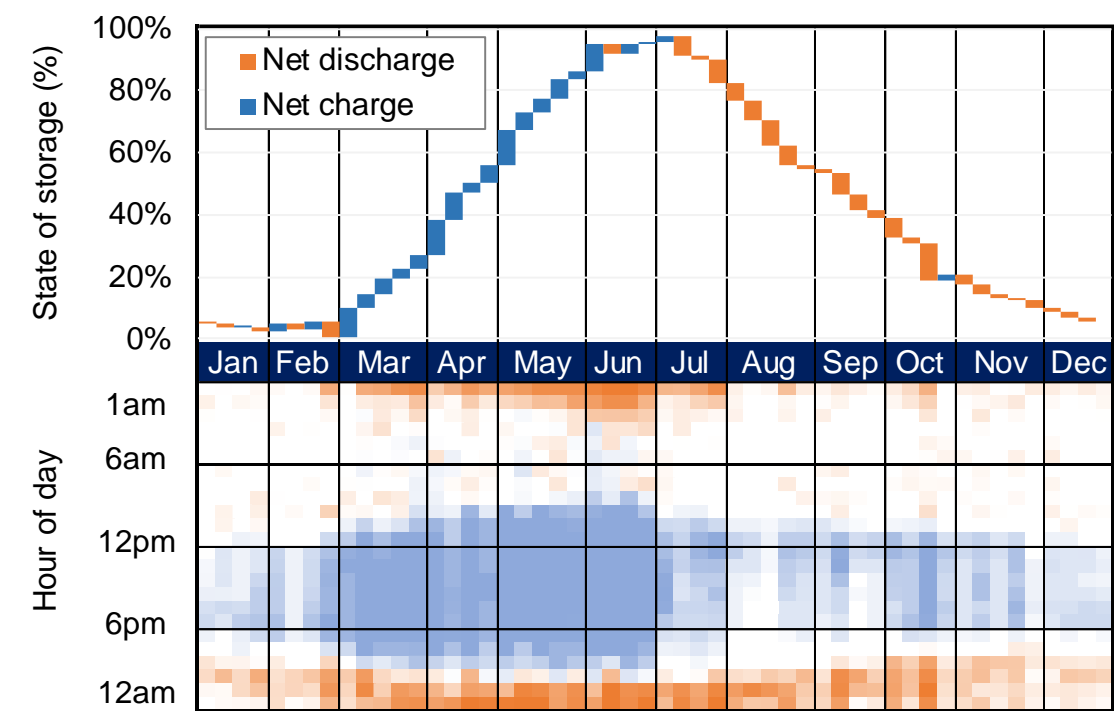
Example Case: CSP + solar thermochemical looping



Updated analysis is needed to reflect current SOA in both CSP and solar thermochemical H₂

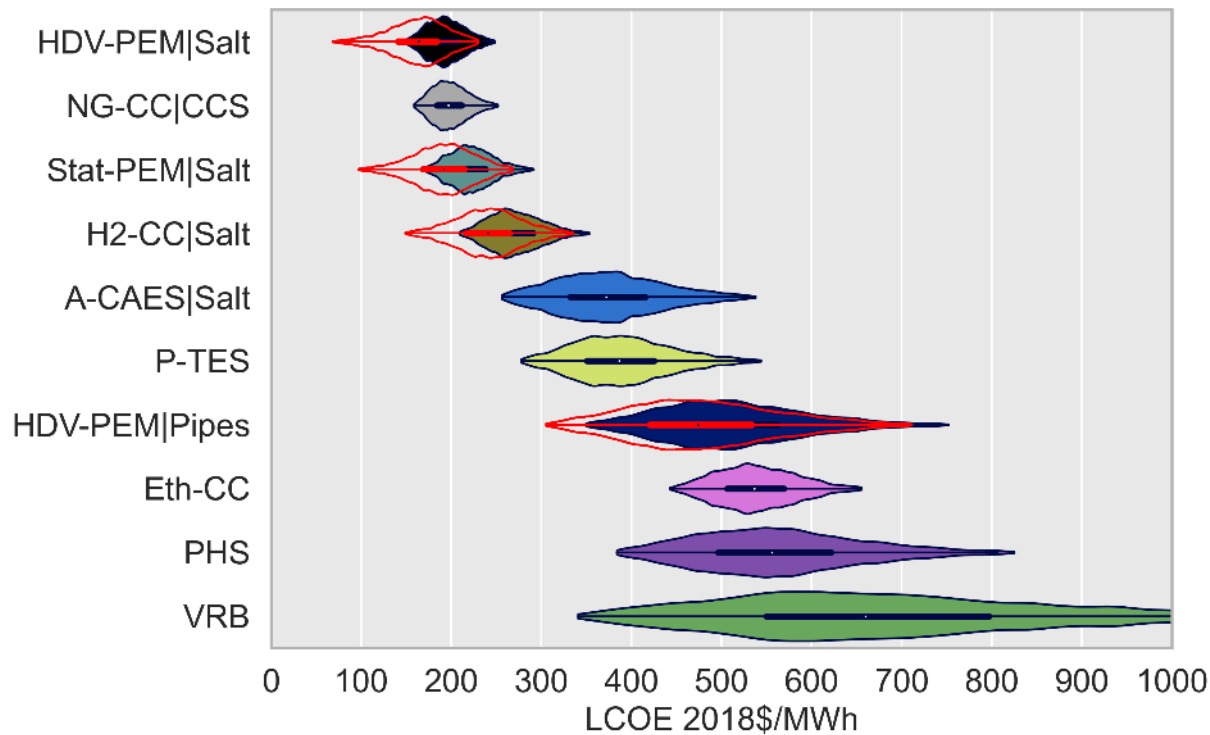
Potential for Long Duration Energy Storage

Modeling of 85% renewable grid in Western Interconnect to inform energy storage capacity factors



Example capacity factor for technology with 40% round-trip efficiency

Analysis of current and future costs for long duration energy storage



Monte Carlo analysis of future costs

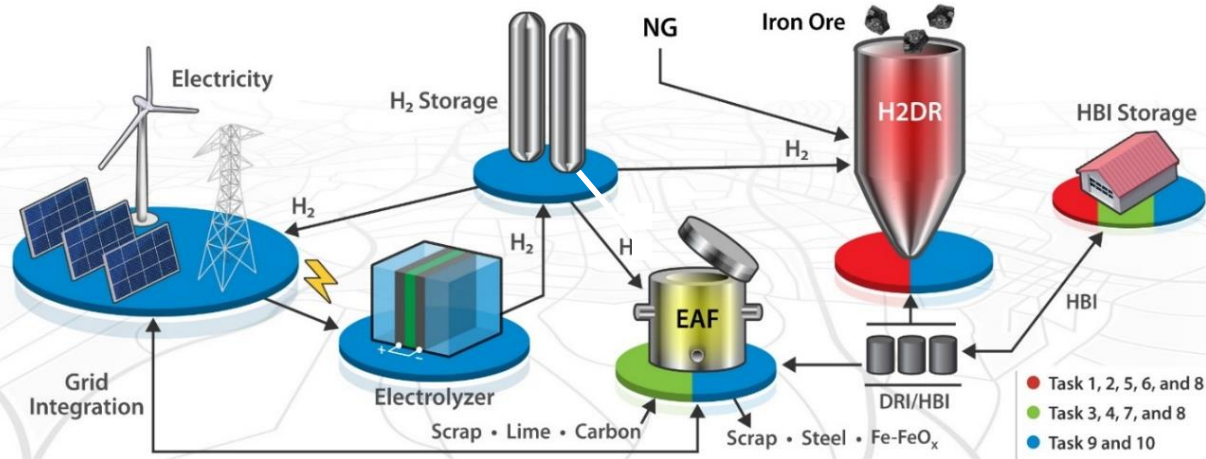
Hydrogen technologies are among the five lowest cost pathways for multi-day energy storage

Analysis led by DOE-Strategic Analysis and co-funded with Solar Energy Technologies Office and Wind Energy Technologies Office.
Grid modeling informed by EPRI and five member utilities. For more information, please see: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3720769

Integration with Industrial & Chemical Processes

Decarbonizing Iron/Steel Production with Hydrogen (HySteel projects)

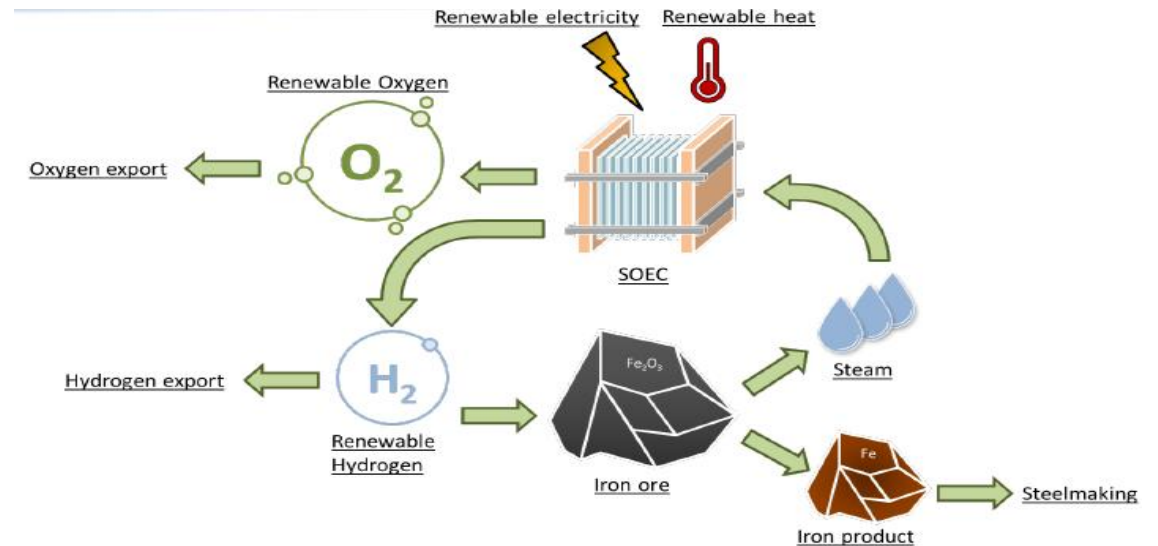
Missouri U. of S&T - Grid Interactive Steelmaking with H₂ (GISH)



Project Goals:

- 1 ton/week iron production using variable H₂/NG content; scaled to 5,000 ton/day
- Demonstrate grid integrated steel production system combining:
 - H₂-Direct-Reduction furnace for ironmaking
 - Electric melting for steelmaking

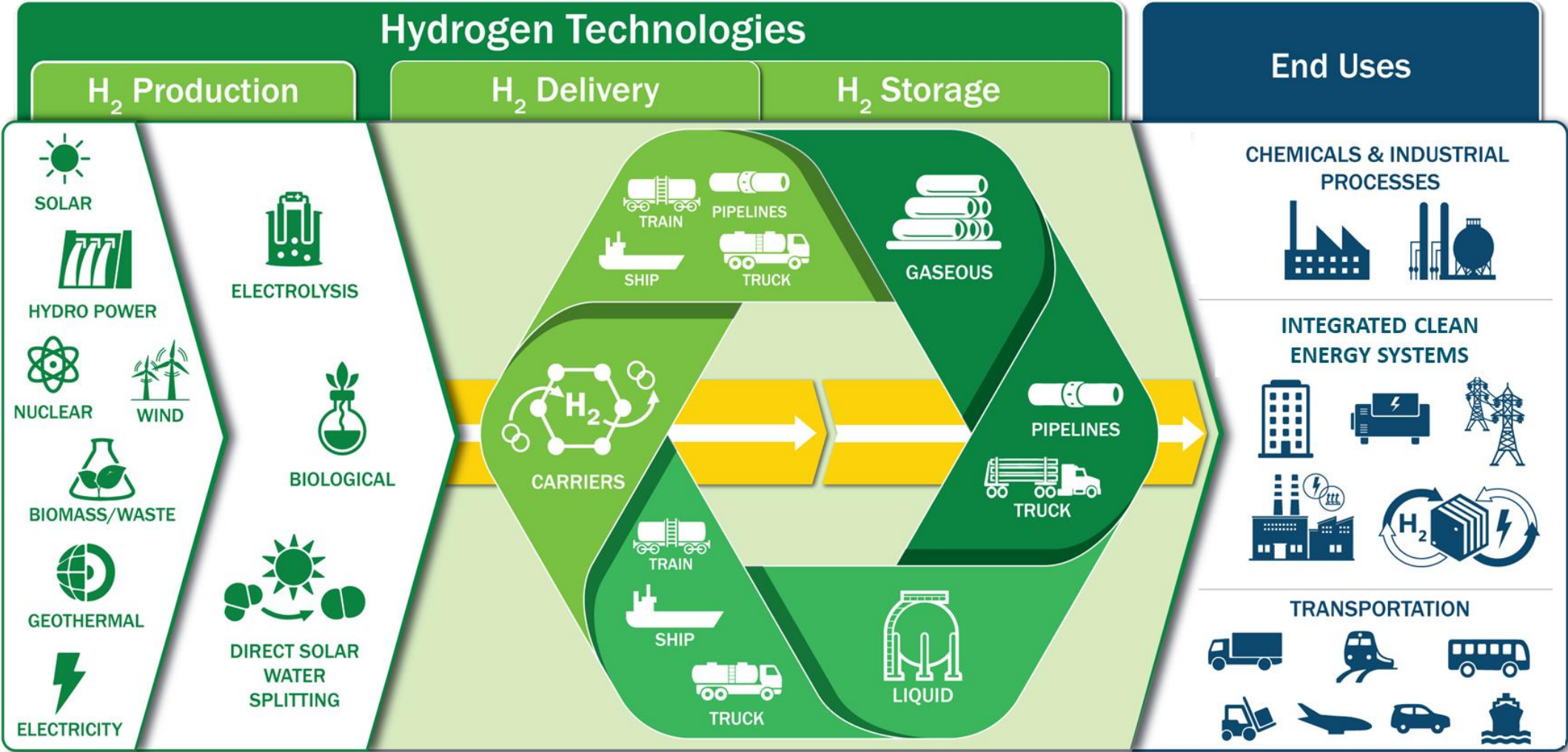
U. of California Irvine - H₂ SOEC integrated with Direct Reduced Iron (DRI) plants



Project Goals:

- 1 ton/week equivalent H₂-Direct-Reduction pilot system, scale-up design for a 2Mton/year DRI product capacity
- Demonstrate a thermally & chemically integrated Solid Oxide Electrolyzer system with a DRI plant

The Big Picture for Clean Hydrogen Production and Utilization



Optimized co-located integrated systems help to mitigate delivery infrastructure costs

Ways to Connect – Events, Resources and Career Opportunities

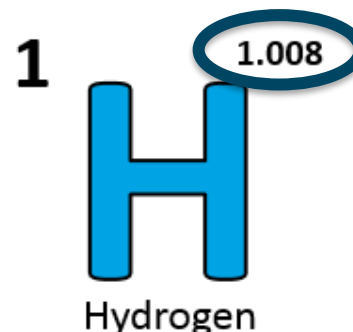
Save the Date

June 6 to 9, 2022:

**DOE Hydrogen Program
Annual Merit Review and
Peer Evaluation Meeting
(AMR)**

Oct 8 - Hydrogen and Fuel Cells Day

- Held on hydrogen's very own atomic weight-day
- DOE EERE comms campaign all week



Open ORISE Fellowships

- Fuel Cells (2 positions):
 - [DOE-EERE-STP-HFTO-2021-1800](#)
- Hydrogen Production:
 - [DOE-EERE-STP-HFTO-2020-1804](#)
- Hydrogen Infrastructure:
 - [DOE-EERE-STP-HFTO-2020-1804](#)

Apply at [zintellect.com](https://www.zintellect.com)

<https://www.zintellect.com/Opportunity/Details/DOE-EERE-STP-HFTO-2021-1801>



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Thank You!

Dr. Eric L. Miller

Senior Advisor, Hydrogen and Fuel Cell Technologies Office

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hydrogen.energy.gov